

## ORBITER PROCESSING FACILITY SERVICE PLATFORM FAILURE AND REDESIGN

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THE MISHAP

On March 8, 1985, in high bay 2 of the Orbiter Processing Facility (OPF) at the Kennedy Space Center, technicians were preparing the space shuttle orbiter Discovery for rollout to the Vehicle Assembly Building (VAB). A service platform, commonly referred to as an "OPF Bucket" was being retracted when it suddenly fell, striking a technician and impacting Discovery's payload bay door. A critical component in the OPF Bucket hoist system had failed, allowing the platform to fall. The incident was thoroughly investigated by both NASA and Lockheed Space Operations Co., revealing many design deficiencies within the system. This paper reviews the deficiencies and the design changes made to correct them. See Figures 1-14.

THE MECHANISM

The OPF Bucket system, Figures 1 & 2, consists of a pair of work platforms, telescoping tube assemblies, hoisting systems, and trolleys, both suspended from a common overhead bridge. Each orbiter payload bay may be accessed by two separate bridges, for a total of four Buckets per high bay.

THE WORK PLATFORM is made of aluminum, with a work area of 1 x 3 meters. A technician located in the Bucket has a hand operated rotation device with which he may rotate the Bucket one to two full revolutions. The first production set of OPF Buckets uses a chain drive system that allows the Bucket to rotate two revolutions but requires locking the Bucket into position after rotation. A later set of OPF Buckets uses a worm gear drive device which is self locking but rotates only one revolution. At the time of the mishap the Buckets had a rated capacity of 225 kg and were connected to the hoisting system thru the rotation device. An electrical control station, Figure 3, is available in the Bucket which controls the direction (up/down, east/west, and forward/aft) and speed (3 meters/min. and 1 meter/min.) of the Bucket motion drives.

THE TELESCOPING TUBE ASSEMBLY consists of four nested square steel tubes each 2.75 meters long allowing the Bucket to lower 6 meters into the orbiter payload bay. The telescoping tubes carry torsional loads preventing the Bucket from rotating in the horizontal plane and carry bending moments

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preventing eccentric loads from tipping the Bucket in the vertical plane. The tubes do not provide vertical support. The smallest of the tubes is 250 mm square and connected at its bottom to the Bucket thru the rotation device, the upper end of the tube has a travel stop which engages intermediate tubes above it. The two intermediate tubes, one 300 mm and the other 350 mm square, have bronze guides and travel stops which engage their adjacent tubes. The fixed upper tube is 400 mm square and is directly connected to the trolley chassis.

THE HOISTING SYSTEM, Figure 4 & 7, raises, lowers and provides vertical support for the Bucket and telescoping tubes. A two part reeved, dual wire rope hoist system using a commercial, off the shelf, wall mounted, 1350 kg capacity, AC electric hoist is used.

At the heart of the system is the hoist which has full depth, 20 degree involute, modified tooth form, straight spur gears, machined integrally with or splined to their shafts. The modified tooth form allows high addendum, small pitch diameter pinions, with higher strength teeth, to be used with low addendum gears more closely matching gear and pinion tooth strength and preventing undercutting of the pinion teeth. The hoist has an electrical solenoid operated drum type holding brake attached to its motor and an automatic Weston screw-and-disc type load brake mounted between the first and second gear reductions in the gearbox, Figure 5. The Weston load brake holds the load regardless of whether the power is on or off. When lowering the load the motor applies torque to the load brake causing the disc to unscrew and thus slip, allowing the load to lower. When raising, the motor causes the disc assembly to screw together, tightening the assembly. A ratchet pawl engages a ratchet on the disc preventing the load from backdriving when stationary.

The hoist is mounted to the outside of the fixed 400 mm upper tube and has two 10 mm stainless steel wire ropes anchored to its drum. The wire ropes pass through an upper snatchblock attached to the top of the fixed tube and, at the time of the mishap, routed down thru the telescoping tubes to a lower snatchblock attached to the Bucket rotation device. The rope is routed through the lower snatchblock terminating at the upper end of the fixed tube. With the two part reeving the hoisting system has a rated lifting capacity of 2700 kg.

THE TROLLEY provides support and east/west motion capability for the Bucket and telescoping tubes. It is a steel frame chassis with a commercial, underhung, four wheel trolley unit at each corner of the frame. Two of the wheeled trolley units have electric drive motors and geared drive wheels.

THE BRIDGE is a steel truss which supports two trolley/Bucket assemblies and provides the forward/aft motion capability of the system. The electric drive motor and gear box are centrally located on top of the truss, connected to drive shafts running to each end of the truss; chain drives connect the drive shafts to the drive wheels, Figure 6. The

bridge also has a control station that can control hoist, trolley and bridge drives for each bucket.

#### THE CAUSE OF THE MISHAP

The direct cause of the mishap was a failure of a hoist system master link, Figure 7, allowing the bucket to fall, Figure 8. The master link attached the lower snatchblock to the Bucket and was probably broken by locking up the Bucket's vertical hoisting system. The locking up resulted from the Bucket being raised until the telescoping tubes had reached their upper travel limit and were physically prevented from further motion. The hoist continued to drive applying an increasingly large force to the lower snatchblock and master link assembly causing the master link to break. An electrical limit switch designed to shut off power to the hoist prior to the tubes reaching their upper travel limit had been misadjusted and did not engage, Figure 9. The hoist system was designed to have redundant wire ropes, lower snatchblocks and master links loaded in parallel.

An earlier failure of one of the master links had occurred at which time the Bucket was removed from service and "Do Not Operate" tags were attached to the Bucket control stations. The mishap occurred upon failure of the second master link after the Bucket was tagged out. The primary cause of the mishap was attributed to operator error due to unauthorized use of the tagged out Bucket.

Investigation by NASA, Lockheed Space Operations Co., and a Lockheed Corp. protection consultant revealed many design related deficiencies with the OPF Bucket's hoisting and positioning mechanisms. These deficiencies were significant and if not corrected would have probably lead to another mishap. Below is a summary of these deficiencies.

1. The OPF Bucket system lacked a mechanical lock that would support the system and prevent its inadvertent use.
2. The system lacked an operational up travel stop switch thus allowing the Bucket operator to use the limit switch as an the operational stop. The system lacked any device that would indicate a failure of the limit switch.
3. The system was not provided with an overload protection device.
4. Main load carrying components were inaccessible and could not be readily inspected.
5. The electrical control system operated differently for the first production set of OPF Buckets than it did for the second production set.
6. The design of the control station switches would cause them to stick in the energized position after repeated use.
7. There were no visual aids to help the operator determine when he was

approaching the end of travel of the hoist system.

8. Inadequate clearance existed between the bottom of the OPF Bucket and the orbiter payload bay doors when the doors were being closed. This required the operator to retract the Buckets until the limit switch was reached.

9. The load capacity limit for the OPF Bucket was inadequate to support normal operations.

10. The master link failed at less than its rated capacity.

11. Other hoist system overload modes existed such as telescoping tubes which could bind then release and fall causing impact loads to the system. Bucket handrails could bottom out on other structures during retraction if the Bucket was not rotated to the proper orientation.

12. Downward overtravel could cause the hoist wire rope to rewind in the opposite direction on the hoist drum and cause the hoist load brake to be ineffective.

#### THE NEW DESIGN

Personnel and flight vehicle safety was the primary concern in the redesign effort. The design changes to correct the deficiencies in the system were not limited solely to beefing up the failed components but included a wide scope of changes including: improved maintenance capabilities, improved operation, increased load carrying capacities, electrical control reliability and safety enhancements. Improvement in reliability and the elimination of single failure points were also main goals of the redesign.

A review of OSHA and ANSI specifications revealed that there were no government or industrial standards for this particular type lifting mechanism. There were specifications for similar devices, however, such as exterior building maintenance platforms, typically used by painters and window washers for access to the outside of buildings. These specifications required that the platforms be maintained in a horizontal position with the failure of one of the hoisting ropes, that minimum safety factors of 10:1 be provided on the hoisting system and that the system have no single failure points. The new design would comply with the intent of these specifications.

INTERIM CHANGES were made immediately following the mishap to prevent a recurrence of the failure and allow returning the Buckets to service under restricted use. The changes included:

1. Redundant limit switches were installed at the upper end of the telescoping tubes. The switches were placed in series with the first switch located 45 mm below the physical upper travel limit and the second located

25 mm below the limit. The switches were also reoriented to eliminate the misalignment problem which contributed to the mishap. The change in alignment can be seen in Figures 9 & 13.

2. Visual aid stripes were painted on the telescoping tubes. The stripes are visible to the operator and when aligned indicate that the travel limit is being approached.

3. Inspection holes were cut in the lower end of the 250 mm telescoping tube allowing easy access and inspection of the master links and snatchblocks.

PERMANENT MODIFICATIONS were made to the system after completion of the mishap investigations that were intended to correct the design deficiencies identified by the various mishap investigation committees. An extensive failure modes and effects analysis was performed which identified system single failure points, latent failure points and hazards which were corrected where possible. Latent failure points, such as a failed-closed upper limit switch, are failure points in redundant systems in which the failure would be undetectable during normal use. These points were required to be inspected on a periodic basis if they could not be removed by design. The inspection requirement assured that if any failures occurred they would not go long undetected.

The importance of operator and user involvement in the redesign effort cannot be overemphasized. A key element in the redesign effort was the use of interviews by the design engineers with the Bucket operators. The operators knew the system well and had valuable information on how the system should be configured to suit their needs.

Inspection of the telescoping tube travel stops revealed damage caused by the tubes binding then working loose, freefalling and impacting the stops. Methods to individually drive each tube with jackscrews or wire ropes were rejected as being difficult to control and requiring too much space. It was decided that a method to control the fall of the tubes would be more practicable. The tubes if they should hang up would be allowed to fall but the descent velocity of the fall would be limited.

The selection of the descent control device involved trade off studies of different concepts including hydraulic cylinders and centrifugal brake type devices. The hydraulic cylinder concept appeared initially to be the most promising since the descent velocity could be controlled simply by selecting the correct size orifice for each size telescoping tube and the orifice size could be varied with ease. Problems with differing hydraulic fluid volumes between the downstroke and upstroke and concerns with the possibility of contaminating Space Shuttle payloads with leaking hydraulic fluid led to the rejection of the hydraulic cylinders as descent control devices.

The system finally selected was a commercial load control brake which

is actually a personnel escape device used by construction workers to jump off buildings in emergency situations. The device has an internal centrifugal brake that will limit angular velocity similar to the rotary dial in a dial type telephone forced in the counterclockwise direction. The load control brake is attached to the trolley chassis with an 8 mm wire rope routed down through a pulley on the telescoping tube, and back up to terminate at the trolley chassis, Figure 10.

A load sensing device, Figures 11 & 12, was installed that would sense high or low hoist loads and shut off power to the system. A load equalizing bar was also installed to maintain equal loading of the 10 mm wire ropes.

The hoisting system components, Figure 11 & 13, were repositioned to allow access for inspection of the wire ropes and wire rope pulleys. The lower snatchblock and master link assembly were eliminated.

To prevent inadvertent operation of one Bucket by an adjacent Bucket operator the control system circuitry was reconfigured. The Buckets in both OPF high bays were made to operate identically.

A study of the hoist revealed that the load control brake ratchet pawl stop, item 34 in Figure 5, a hex head screw, was located adjacent to the gearbox oil drain plug, item 33 in Figure 5. The two could be easily confused and inadvertent removal of the brake ratchet pawl stop would cause the brake to become nonfunctional. Labels were attached to the drain plug and the ratchet pawl stop bolt was sealed to the gearbox case.

Shunt trip circuit breakers were installed and mounted in a locked cabinet. Once tripped the circuit breakers cannot be reset without unlocking the cabinet. The circuit breakers are wired to the upper limit switches and to the load sensing switch. A tripped circuit breaker will indicate that there is problem with the system and that inspection or repairs are required.

Concepts are now under study to eliminate single failure points in the gear train of the commercial hoist. Concepts being considered are replacing the existing hoist with a commercial hoist that has no single failure points, installing a brake on the drum of the existing hoist or installing an inertia reel type load brake between the Bucket and the support structure. Control systems for telescoping tubes which could be used in lieu of the descent control devices are being investigated. Results of these studies are expected by the second or third quarter of 1988.

#### TESTING

Tests were conducted to verify that the load control brake used to control the descent of a falling telescoping tube would function correctly, and, that the hoist system components breaking strength ~~was~~ as assumed.

To test the load control brakes a full scale simulator, Figure 14, was

built to simulate the 350 mm telescoping tube and trolley chassis. Load cells were installed at the four corners of the trolley chassis, where the wheeled trolley units are located, to measure trolley loads and at the load brake wire rope termination to measure load brake loads. A linear transducer, "fish reel pot" was installed at the bottom of the telescoping tube to measure displacement and velocity. The telescoping tube was allowed to freefall with the load control brake connected and the loads at the trolley measured during impact of the tube travel stop. All load control brakes are qualification tested in this manner prior to installation on an OPF Bucket.

A failure test of the wire rope pulleys, Figure 13, and load limiting switch assembly, Figure 12, was conducted to verify that the manufacturers rated breaking strength was valid for the configuration in which they were being used. The test results confirmed that the weak link in the system was not the wire rope, which was analyzed as the weakest element, but the load limiting switch. The switch failed at 95% of its rated breaking strength. The test did confirm that adequate safety factors were provided for the system.

### CONCLUSIONS

There are many lessons to be learned from the OPF Bucket failure, the most important of which is that equipment can be misused and probably will be if it does not meet the needs of its user. Design engineers must solicit the opinions and needs of the people who will use and operate the mechanisms that they design.

Latent failure points should be identified and dealt with, a failure in a redundant system that goes undetected in turn creates a single failure point. Often a latent failure point may be worse than a single failure point because it may instill a false sense of security in the system.

The failure of the master link at less than its specified breaking strength is an example of a manufacturer's desire to get the most from his product. In this case the rated breaking strength was based on unpublished test conditions. These conditions were not only omitted from his catalog and engineering design manuals, but were not even common knowledge of his engineers. When critical systems are involved it pays to test the components to determine their limitations.

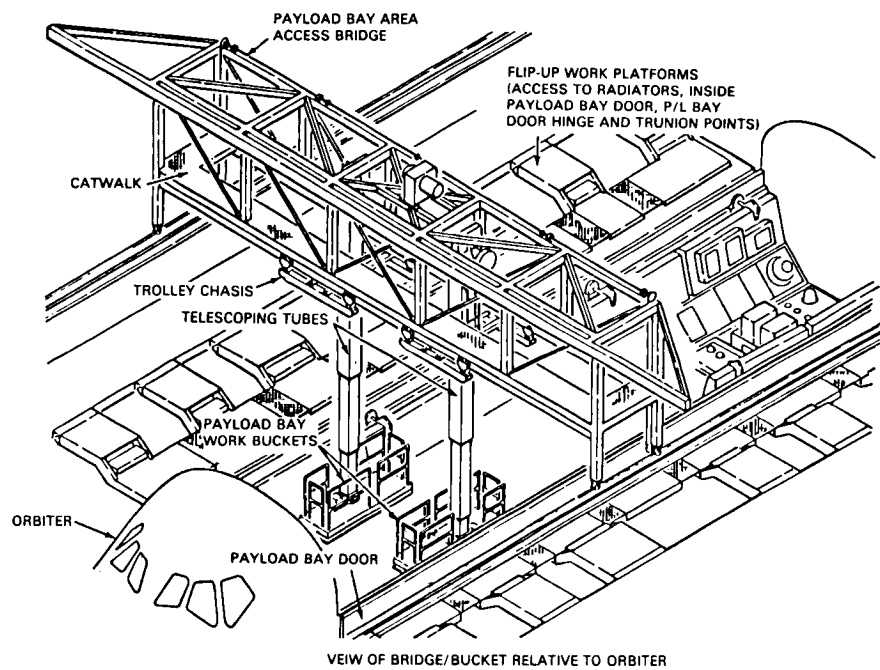
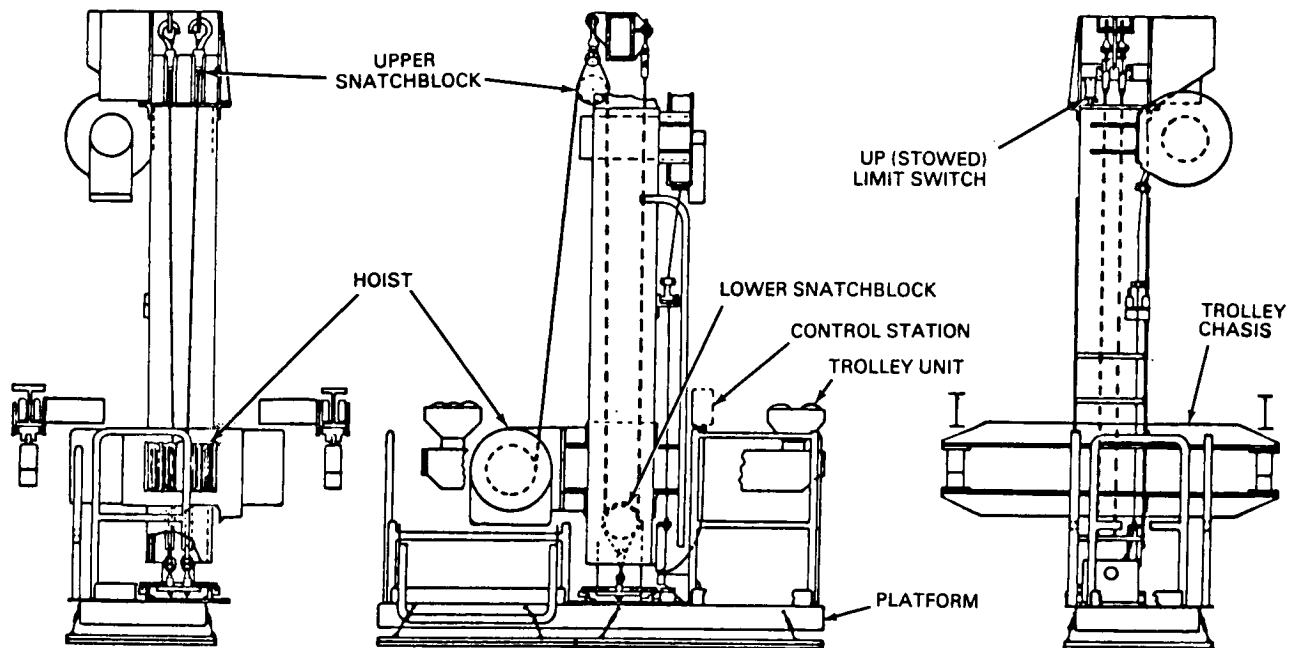


Figure 1

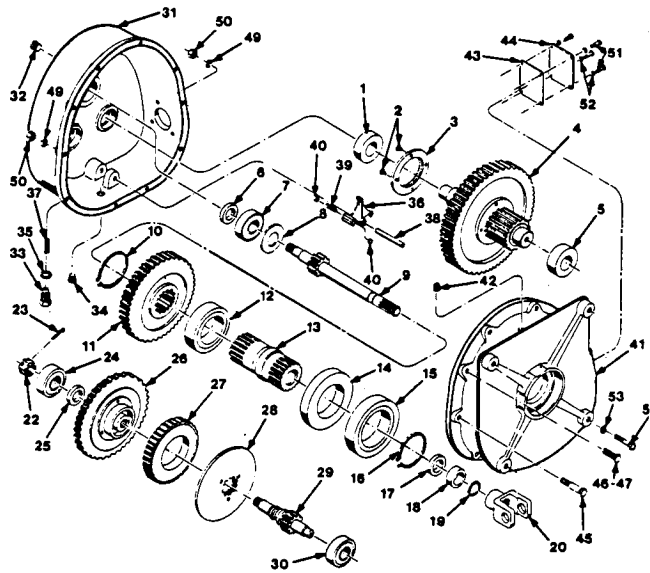


OFF BUCKET ASSEMBLY

Figure 2







HOIST GEARBOX EXPLODED VIEW

Figure 5

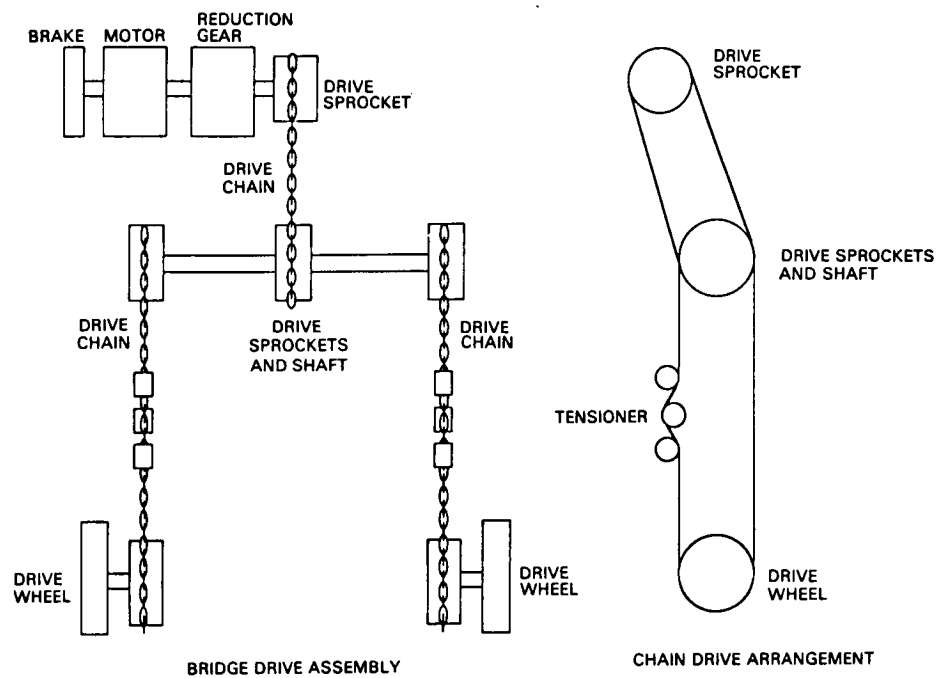


Figure 6

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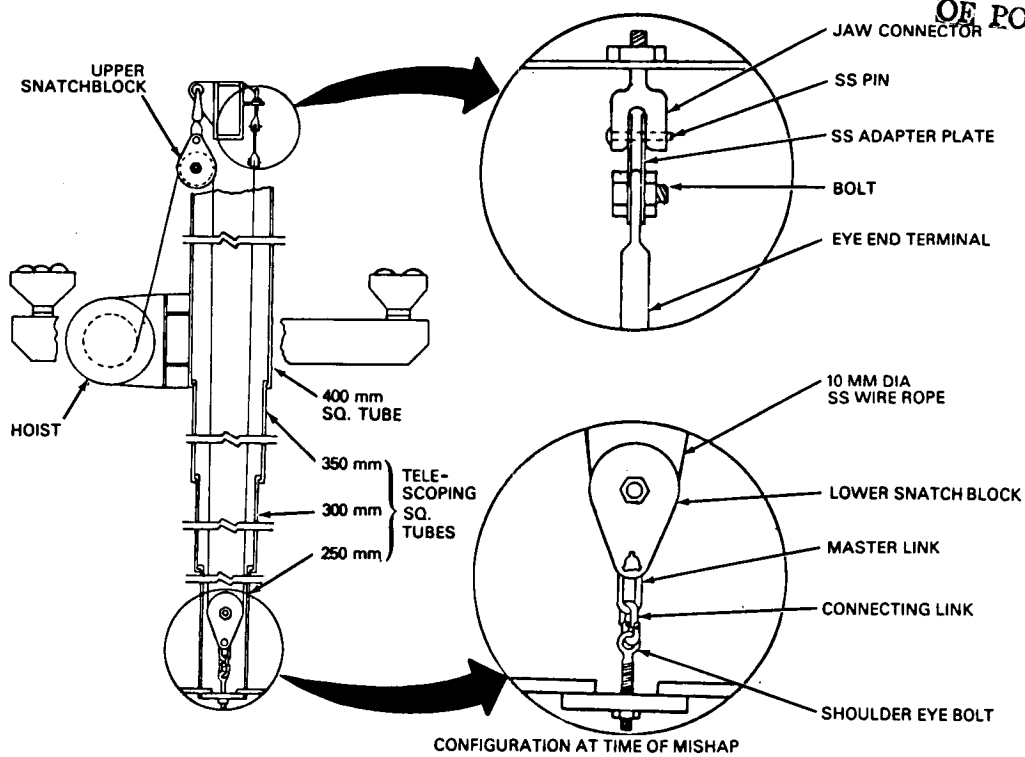


Figure 7

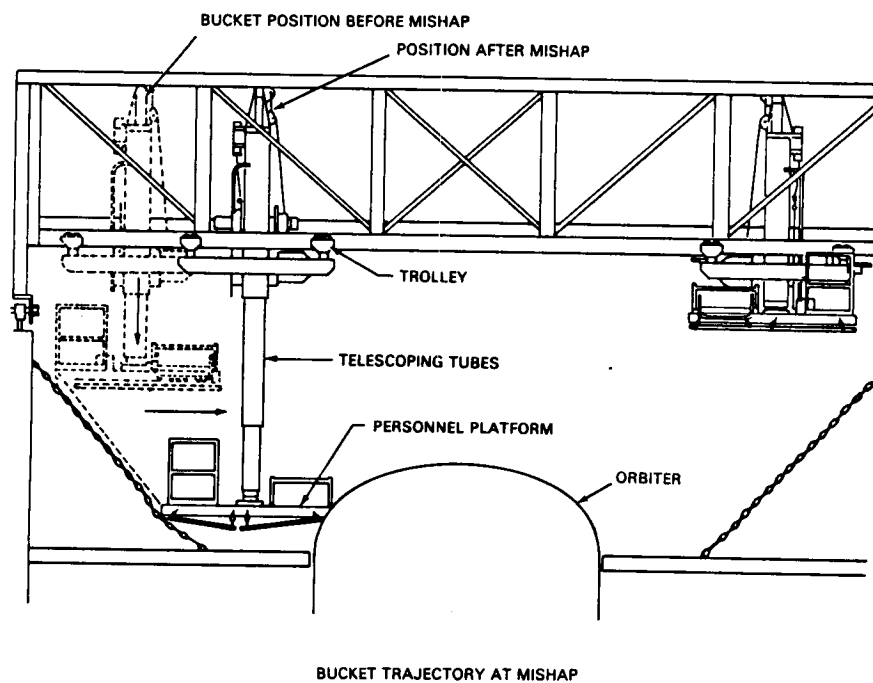
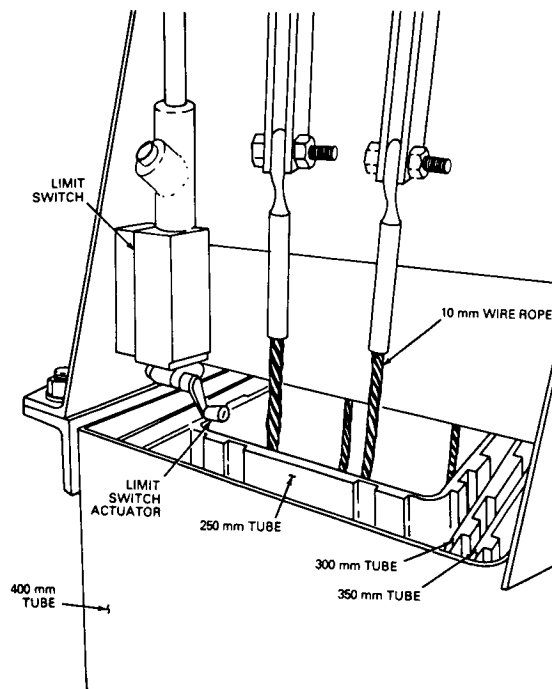
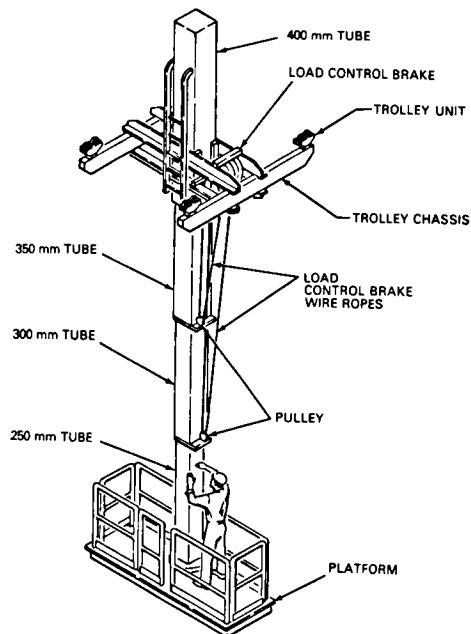


Figure 8



LIMIT SWITCH CONFIGURATION AT TIME OF MISHAP

Figure 9



OFF BUCKET WITH LOAD CONTROL BRAKE

Figure 10

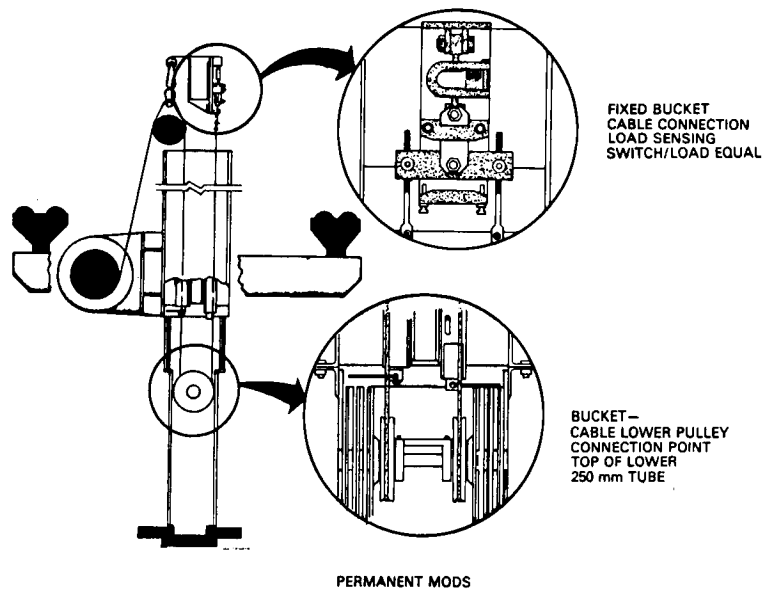


Figure 11

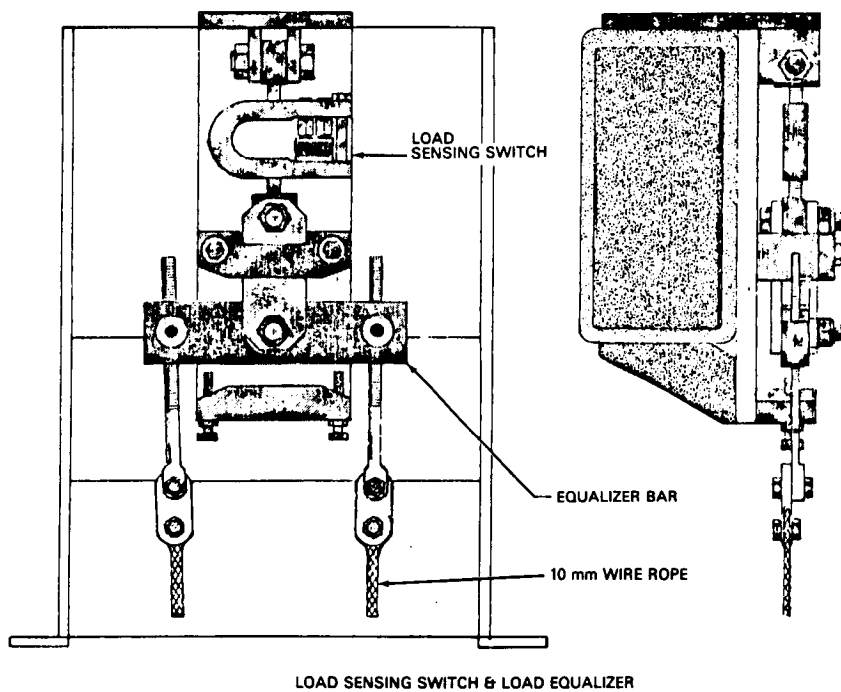
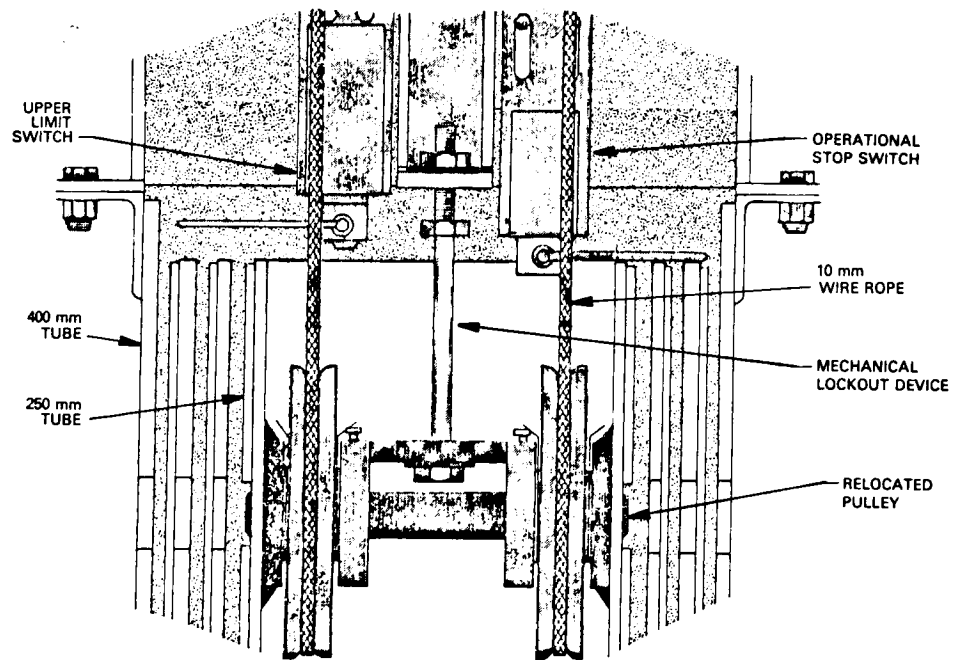


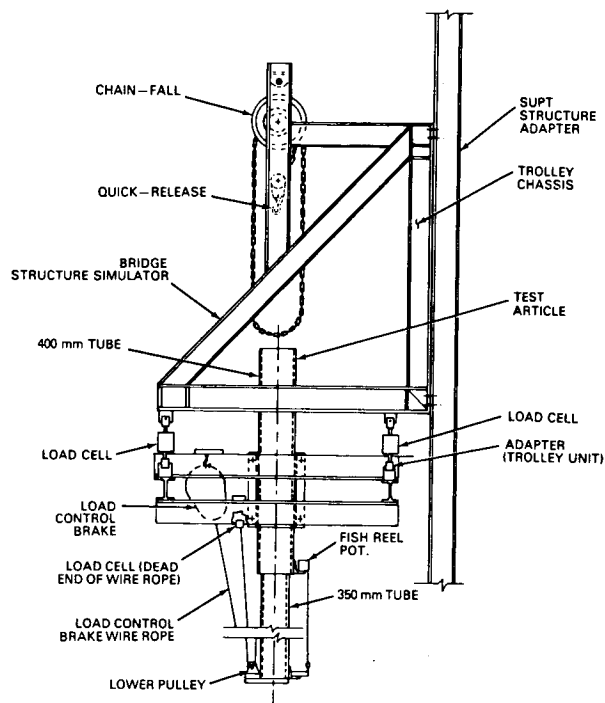
Figure 12

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LOWER PULLERS, REDUNDANT LIMIT SWITCHES & MECHANICAL LOCK

Figure 13



LOAD CONTROL BRAKE TEST RIG

Figure 14